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Scientific Systems

AUTOMATIC RENDEZVOUS AND DOCKING SYSTEMS FUNCTIONAL AND PERFORMANCE REQUIREMENTS

DRL ITEM SE-1169T

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1.0 Intoduction and Summary

A number of alternative approaches to rendezvous and proximity operations activities have been proposed, and in some cases demonstrated, in various manned spaceflight programs from Project Gemini to the Space Shuttle. These operations have generally been limited in scope, and frequently depend heavily on ground support facilities and personnel for both planning and execution. The difficulty of automating these activities, and the resulting system performance requirements, are strongly influenced by the operational techniques employed, and by the range of prospective operations to be carried out.

An examination of the Orbital Maneuvering Vehicle Phase B design reference missions reveals that as a group, they have the following characteristics and implications for automated systems and operations:

a. They encompass a broad spectrum of operational activities ranging from servicing and repair of low earth orbital platforms, to retrieval and emplacement of payloads at altitudes of up to 1000 nautical miles;

b. Nine out of ten missions involve at least one rendezvous, and seven out of ten involve two or more;

c. Mission design techniques must take explicit account of differential nodal regression effects between the point of origination, target, and point of termination;

d. Mission operational techniques must be capable of hand-day-of-mission dispersions away from nominal conditions without radical revision of the operational plan;

e. A significant possibility exists that large software development costs will be incurred for design of phase-specific guidance and control functions, unless a unified approach to guidance and control can be devised;

As a result of these considerations, the contractor has developed a generalized mission design scheme which utilizes a standard mission profile for all OMV rendezvous operations, recognizes typical operational constraints, and minimizes propellant penalties due to nodal regression effects. This scheme has been used to demonstrate a unified guidance and navigation maneuver processor (the UMP), which supports all mission phases through station-keeping. Section 2.0 describes the approach to OMV operations analysis; a description of the resulting mission design system is contained in Section 3.0, together with an example of its application to the Large Observatory Servicing Mission, which is typical of OMV rendezvous operations. The initial demonstration version of the Orbital Rendezvous Mission Planner (ORMP) has been provided to the customer for evaluation purposes, and program operation will also be briefly discussed.

Changes and additions to the BETELGEUSE basic simulation program have incorporated the Unified Maneuver Processor (UMP), the derivation and implementation of which is contained in Section 4 and Appendix A. Both the ORMP and UMP emphasize the pertinence of the opening statement of this section that the choice of operational technique is critical to the automation problem, especially as regards on-board software overhead and associated development costs.

2.0 Requirements Analysis

Table 2-1, taken from the OMV Technical Requirements Document (1), summarizes the early OMV design reference missions. As stated earlier, of these ten missions, all but one involve at least a final rendezvous with the Orbiter, and seven require an initial rendezvous with a platform. In addition to the explicit plane change requirements, very large out-of-plane components arise at some point in missions 1, 2, and 6 due to differential nodal regression. As much as 1000 or more feet per second is exhibited in Mission 6. It is also noted that these missions all return to their initial starting point, the Orbiter, which implies that the second rendezvous design is constrained by the target orbit, and the deployment orbit of the shuttle. It can be anticipated that unless a system such as GPS is available, large navigation errors will occur between major burns, and that even with GPS, application errors will cause significant dispersions at the targeting end points. In either case, it seems that as many as three mission phases may be required:

MISSION TITLE	RENDEZVOUS PAYLOAD	RENDEZVOUS ORBITER
Large Observatory (1)	350 x 350	160 X 160
Payload Placement (2)		160 x 160
Payload Retrieval (3)	378 x 378 1 deg p/c, WTR launch	160 x 160
Payload Reboost (4)	260 x 260 inplane reboost to 370	160 x 160
Payload Deboost (5)	160 x 160 deboost to entry	160 x 160
Payload Viewing (6)	1400 x 1400 1 deg p/c each way	160 x 160
Subsatellite (7)	___________	160 x 160
Multiple Payload (8)	270 x 270 deploy payload at 245	160 x 160
Upper Stage (9)	OMV derivative stage no retrieval required	
Early Limited Servicing (10)	as required within capabilities	160 x 160

Table 2-1: Initial OMV Design Reference Missions

i) Initial boost, gross phasing, and out-of-plane correction to an offset point in phase and altitude;

ii) Final boost, phasing, and out-of-plane corrections to reremove the major effects of accumulated navigation errors and dispersions;

iii) Terminal area operations aided by vehicle-to vehicle navigation, leading to the conclusion of the rendezvous phase.

These mission phases are fairly generic to all rendezvous operations, dictated by the physical limitations of on-board actuators and sensors. They do not of themselves prescribe a particular approach to mission design and operations. Additional requirements which must be taken into account in developing an approach to automated operations fall into three general categories: 1) those dictated by the automation objective itself; 2) those enforced by a desire for consumables economy and minimal demands on sensors and subsystems; and 3) safety and operability issues in the terminal proximity operations zone. The implications of

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(1) RFP 8-1-4-PP-02142, 3 January 1984, Attachment A, pp. 21-23

these constraint categories will be summarized in reverse order, as they tend to determine the functional requirements on the automated system, which is the ultimate topic of this section.

SAFETY AND OPERABILITY

-Control of terminal phase approach direction and braking offset, so as to protect payloads from accidental collision and plume impingement, and facilitate the acquisition of stationkeeping and docking sensors.

-Control of terminal phase arrival time so as to permit visual monitoring of the final approach and subsequent proximity operations activity.

-Control of the maneuver times so as to assure the operability of optical sensors for navigation support, and permit monitoring of burn computations and applications.

-Graceful performance degradation in the face of off-nominal initial conditions and sensor failures.

ECONOMY AND PERFORMANCE REQUIREMENTS

-Placement of maneuvers at or near the optimal times for maximum efficiency, particularly at nodal crossing points.

-Predictability of the pre-terminal phase conditions so as to limit the tracking range requirements of RF sensors.

AUTOMATION REQUIREMENTS

-Capability to handle off-nominal dispersions without redesign of the maneuver plan.

-Feasible software implementation requirements.

It is not necessary to search any farther than the Apollo/Skylab concentric flight plan technique to find an operational strategem which meets all of the above requirements, with the exception of automated stationkeeping. This will be dealt with later, after an exposition of the design technique afforded by CFP, and the resulting approach to aumated mission design and automated orbital operations. Since it is the terminal conditions of the operation that are ultimately of interest, we begin with the design of the terminal phase, and proceed backward to the initial conditions.

TERMINAL PHASE

Under a previous contract (2), the conditions for a minimum propellant transfer to a coelliptic offset from a target have been derived. For the special case where the initial orbit is coelliptic with the target orbit, it can be shown that the sum of the thrust directions at transfer and braking add up to 180 degrees, in the target local vertical system. Furthermore, if the final approach to the target is from an elevation of -26.72 degrees as seen from the target, the transfer maneuver will be along the current line-of-sight at TPI, and the trans-

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(2) Multi-body Proximity Operations GN&C Analysis Program, Software Requirements Document, Appendix B, Contract NAS9-16896, 1 Dec 1983.

fer interval is 151.75 degrees of orbit travel. These conditions are independent of orbital altitude or initial range, providing the transfer is accomplished upon the appearance of the 26.72 degree elevation. Since it is desireable to minimize excursions away from the track attitude for performing efficient maneuvers, it seems reasonable to adopt these as the nominal conditions for a terminal phase. If the time of arrival is fixed to be shortly after local sunrise, and the rendezvous is from below, the target will be illuminated from behind the interceptor during the final braking phase. An entirely serendipitous benefit of this choice results from the fact that in low earth orbit, the transfer interval is almost exactly the maximum duration of a nightside pass, so that target sunset occurs at approximately the time of transfer, which is the optimum sun illumination angle for optical tracking in reflected sunlight.

At any given target orbit altitude, the following events can now be fixed in the prospective timeline:

1) TTSR, the time of target sunrise
2) TTPF, the time of braking (=TTSR + DTSR)
3) TTPI, the time of transfer, 151.75 deg of target orbit travel before TPF

The targeting can aim the vehicle to any desired offset in altitude and downrange to avoid plume impingement, and should include several nominally zero midcourse corrections between TPI and TPF.

PRE-TPI TARGETING

In general, it is desireable to guarantee a minimum length of time prior to TPI within which both optical and RF (or other) tracking can be accomplished. The first requirement is taken care of by the previous specification of the TPI conditions, which guarantee target visibility with back illumination immediately prior to TPI. In order to accomodate the second requirement, we specify the minimum interval prior to TPI during which the range to the target must be less than the maximum tracking range of the RF sensor. Since the transfer optimality result used in specifying the transfer phase conditions assumed transfer from a coelliptical orbit, we require that the minimum dwell in the pre-TPI coelliptical phase be given as DTCOE, and that the maximum range at the onset of this interval be given as RMAX. We translate the dwell time into an equivalent arc of orbit travel, WTCOE, and find that the coelliptical phase must begin at least (3/2)*WTCOE*DELTAH in curvilinear distance from the TPI point, since the catch-up rate in coelliptical phase is well known as -(3/2)*W*DELTAH. Since the maximum range at this point has been given, the required values of DELTAH and downrange dis-distance, DELTAS, can be solved for. We assume, for the moment, that the maximum range point corresponds to a coelliptical maneuver. We have thus determined the additional constraints

4) DELTAH at the coelliptical burn
5) DELTAS at the coelliptical burn
6) TIGCOE latest time of the coelliptical burn
7) Four additional conditions, imposed by the requirement to be in-plane and coelliptical

PRE-COELLIPTICAL TARGETING

Conditions 4-7 above completely specify the conditions at the onset of the coelliptical phase. Further specification of the placement and timing of prior maneuvers depends on whether, from a planning point of view, the initial state of the interceptor can be considered unconstrained in some degree. The most readily available degree of freedom at the onset of a rendezvous sequence is the initial phase between the target and the interceptor. Since typical operations of an OMV deployed from either the shuttle or space station fix the orientation and shape of the interceptor orbit, we consider that the OMV possesses sufficient energy relative to the interceptor to select the initial phasing by varying the time of the initial maneuver in the pre-coelliptical phase. The objective of the pre-coelliptical program must therefor be to deal with the existing dispersions, differential altitude, and out-of-plane conditions between it and the target. Operational and system performance constraints inevitably set a limit on the maximum time allowed for the rendezvous phase of the mission. We take this limit, TMAX, as given, and subtract from it the time required for the phases from the coelliptical to the braking maneuver, TTPF-TIGCOE. In the error-free case, the most efficient sequence of maneuvers for creating the required conditions at TIGCOE result from a phasing burn at the largest integral multiple of interceptor orbits prior to TIGCOE which is greater than time zero, followed by a height adjust maneuver 1/2 rev before TIGCOE. At the same time, it must be noted that for large differential altitudes, increasing the total time for the rendezvous sequence will also increase the effects of differential nodal regression, which may either decrease or augment the out-of-plane condition at TIGCOE. The first candidate solution is obtained by noting that TIGCOE is ultimately tied to the times of target sunrise, which repeat each target orbit period, and choosing the latest TIGCOE which does not violate the total time constraint:

1) Choose latest TIGCOE such that TTPF .LE. TMAX;
2) Find the first time of nodal crossing ,TNODE, prior to TIGCOE;
3) Augment the time in the coelliptical phase by DT=TIGCOE-TNODE, and the downrange target by (3/2)*DELTAH*DT*W;
4) Redefine TIGCOE=TNODE;
5) Find the largest integral number of interceptor orbits prior to TIGCOE which is larger than time zero, TIG1;
6) Define TIGNH as being 1/2 rev prior to TIGCOE;
7) Solve for the targets with burns at TIG1, TIGNH and TIGCOE.

The next candidate solution is obtained by repeating this process using the next earlier TIGCOE (one target orbit revolution), until a mimimum of the total propellant for the three burns is found, or until no further reductions in total duration are possible. This procedure guarantees a minimum solution for the total problem under given specification of the initial interceptor orbit, target orbit, and total time allowed.

Further reductions in total propellant may be achieved some of the initial interceptor orbit parameters are free variables in the design prolem. In such cases, the initial inclination or ascending node may be chosen so as to counteract the effects of nodal regression, or the arument of perigee and true anomaly fixed so as to place TNODE at the original value of TIGCOE, and place TIG1, TIGNH and TIGCOE at relative apsides of the interceptor and target orbits.

Once a minimum propellant solution has been determined, a final modification is appropriate if a priori statistics are available on the expected envelope of dispersions, defined as the difference between actual and desired initial condition on the day of execution. The covariance of dispersions should be propagated to TIGCOE, and all maneuvers forward in time by an interval which decreases the initial phase by 3-sigma of the expected up-range dispersion at TIGCOE. This guarantees that any changes in maneuvers due to actual dispersions are in the direction of decreasing relative energy between the initial and final orbits. Also, the mission timeline must provide for a (nominally zero) out-of-plane burn at 1/4 rev before TIGCOE to handle out-of-plane dispersions on the day of execution.

3.0 Orbital Rendezvous Mission Planner (ORMP)

Figure 3-1 presents the input data file for the ORMP, which is identical in format to that for the ORBNAV variant of Program BETELGEUSE delivered under this conTRACT. This program was developed at SSI to demonstrate the feasibility of automated mission design using an approach proven on programs previous to the Shuttle. Of interest in Figure 3-1 are items in the maneuver command file which is set up to construct a two-rendezvous sequence for OMV OMV Design Reference Mission 1. On input to the ORMP, the sign of the variable SGN DH is examined to determine whether the rendezvous is to be from below (<0) or above (>0), and the the minimum range at TIGCOE is given as R-NSR = 12 nautical miles. On cards 4 and 5, the difference between TTIG and TCOE (=1800) is taken to be the minimum time to be spent in the coelliptic phase prior to TPI. H-OFF and S-OFF on card 5 specify that the TPI targeting will aim for .002 n.m. uptrack of the target and along v-bar. The variable DWT on cards 6, 7, and 8 specify degrees of orbit travel at which each of these maneuvers occurs following the the one previous. The braking maneuver of this particular example therefore occurs 139 degrees of orbit travel after TPI. H-OFF and S-OFF specify the same targeting for the midcourses as for TPI. On On card 8, DTSR specifies that braking will occur .05 hours after target sunrise, and DWELL specifies that the next rendezvous cannot be initiated earlier than 1

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                  OMV STATE FOR LARGE OBSERVATORY SERVICING MISSION
   PERIGEE ALT  APOGEE ALT   LONG NODE INCLINATION ARG PERIGEE      PHASE
      159.997      160.000   200.00010    28.30000      .0000P   89.34002


                          ENTER MANEUVER COMMAND FILE
    MNVR TIME=SEC OR DEG  SEC OR DEG  DEL-H (N.M.)    HOR OFFSET(N.M.) T N I Y Z
  1 PHAZ TIG1=      .00 DWT=      00        =   2.000 S-OFF=      .000 1 2 0 1 0
  2 NCC1 TIG2=  2711.48 DWT=  180.00        =    .000     =       .000 1 2 1 1 1
  3 OOP  TIG3=  4074.19 DWT=   90.00        =    .000     =       .000 1 0 0 0 1
  4 COEL TCOE=  5529.54 DWT=   90.00 SGN DH  -2.420 R-NSR=    12.000 1 2 1 1 1
  5 XFER TTIG=  7329.54 DWT=  189.01 H-OFF=    .000 S-OFF=      .002 1 2 1 1 1
  6 M/C1 TTIG=  9408.49 DWT=   49.00 H-OFF=    .000 S-OFF=      .002 1 0 1 1 1
  7 M/C2 TTIG= 10076.05 DWT=   41.00 H-OFF=    .000 S-OFF=      .002 1 0 1 1 1
  8 BRAK TTIG= 10873.86 DWT=   49.00 DTSR =    .050 DWELL=     1.000 1 0 1 1 1
  9 PHAZ TIG1= 10529.37 DWT=   51.47 H-OFF=    .000 S-OFF=      .000 2 3 0 1 0
 10 NCC2 TIG2= 78580.45 DWT=     .00        =    .000     =       .000 2 3 1 1 1
 11 OOP  TIG3= 80032.17 DWT=   90.00        =    .000     =       .009 2 0 0 0 1
 12 COEL TCOE= 81398.87 DWT=   90.00 SGN DH   2.314 R-NSR=    16.544 2 2 1 1 1
 13 XFER TTIG= 83198.37 DWT=  198.13 H-OFF=    .000 S-OFF=      .002 2 2 1 1 1
 14 M/C1 TTIG= 85124.23 DWT=   49.00 H-OFF=    .000 S-OFF=      .002 2 0 1 1 1
 15 M/C2 TTIG= 85742.27 DWT=   41.00 H-OFF=    .000 S-OFF=      .002 2 0 1 1 1
 16 BRAK TTIG= 86480.91 DWT=   49.00 DTSR =    .050 DWELL=      .000 2 0 1 1 1


                 REFERENCE VEHICLE LVLH SQUAREROOT COVARIANCE OF DISPERSIONS
DELTA-H           .180E+04  .000E+00  .000E+00  .000E+00 -.900E+00  .000E+00
CURV DIST         .000E+00  .321E+05  .000E+00 -.950E+00  .000E+00  .000E+00
OUT-OF-PL         .000E+00  .000E+00  .137E+04  .000E+00  .000E+00  .000E+00
H-DOT             .000E+00 -.950E+00  .000E+00  .000E+00  .000E+00  .000E+00
S-DOT(CO)        -.900E+00  .000E+00  .000E+00  .000E+00  .000E+00  .000E+00
Z-DOT             .000E+00  .000E+00  .000E+00  .000E+00  .000E+00  .260E+01


OBSERVATORY STATE(LVLH)      COVARIANCE (LVLH): OBTAIN 2 HOUR FIT, 90 MIN PROP
PERIGEE     349.999  .225E+04  .000E+00  .000E+00  .000E+00  .000E+00  .000E+00
APOGEE      350.001  .000E+00  .810E+04  .000E+00  .000E+00  .000E+00  .000E+00
LONG NODE 198.86190  .000E+00  .000E+00  .101E+04  .000E+00  .000E+00  .000E+00
INCLINATN  28.50000  .000E+00 -.950E+00  .000E+00  .000E+00  .000E+00  .000E+00
ARG PERIG    .00000 -.950E+00  .000E+00  .000E+00  .000E+00  .000E+00  .000E+00
PHASE     110.97800  .000E+00  .000E+00  .000E+00  .000E+00  .000E+00  .132E+01

TARGET 1 RELATIVE PERIOD=  .731643E+05 SEC


ORBITER STATE (LVLH)         COVARIANCE (LVLH): OBTAIN 2 HOUR FIT, 90 MIN PROP
PERIGEE     159.996  .225E+03  .000E+00  .000E+00  .000E+00 -.195E+03  .000E+00
APOGEE      159.999  .000E+00  .155E+04  .000E+00 -.135E+04  .000E+00  .000E+00
LONG NODE 200.00010  .000E+00  .000E+00  .434E+03  .000E+00  .000E+00  .000E+00
INCLINATN  28.50000  .000E+00 -.184E+01  .000E+00  .211E+01  .000E+00  .000E+00
ARG PERIG    .00000 -.234E+00  .000E+00  .000E+00  .000E+00  .272E+00  .000E+00
PHASE      89.34002  .000E+00  .000E+00  .000E+00  .000E+00  .000E+00  .132E+01
```

FIGURE 3-1: Planner Input Data

hour after braking of the first sequence. The same definitions apply to the same variables of cards 9-16 for the second rendezvous, which is a return of the observatory to the initial orbit of the OMV. TTIG of card 16 specifies that the total sequence must be concluded by 27 hours after burn 1 of the first rendezvous. No specification of this limit on card 8 of the first rendezvous is interpreted by the ORMP as freeing the argument of perigee and true anomaly of the OMV to be chosen so as to minimize propellant requirements as described above. Also included in Figure 3-1 are the input initial initial states, covariance of target relative OMV dispersions, and covariance of OMV-relative target orbit uncertainties. Figure 3-2 exhibits the output file where the input values of time, coelliptical targets, and initial orbits have been replaced by those resulting from the ORMP construction of the mission. This This data file may be input to ORBNAV without change for subsequent analysis of the total propellant requirements. Finally, Figures 3-3a and 3-3b summarize the nominal maneuver solutions for the TIG1 through TIGCOE sequence. The method of computation of these solutions will be the subject of the next section.

```
                OMV STATE FOR LARGE OBSERVATORY SERVICING MISSION
PERIGEE ALT  APOGEE ALT   LONG NODE INCLINATION ARG PERIGEE      PHASE
  159.997     160.000   200.00020    28.50001      .00000    89.33934

                      ENTER MANEUVER COMMAND FILE
  MNVR TIME=SEC OR DEG  SEC OR DEG  DEL-H (N.M.)   HOR OFFSET(N.M.) T N I Y Z
 1 PHAZ TIG1=      .00 DWT=     .00       =    2.000 S-OFF=        .000 1 2 0 1 0
 2 NCC1 TIG2=  2711.48 DWT=  100.00       =     .000     =         .000 1 2 1 1 1
 3 OOP  TIG3=  4074.19 DWT=   90.00       =     .000     =         .000 1 ^ 0 0 1
 4 COEL TCOE=  5529.54 DWT=   90.00 SGN DH  -2.420 R-HOR=     -16.71_ 1 2 1 1 1
 5 XFER TTIG=  8608.29 DWT=  188.86 H-OFF=    .000 S-OFF=        .002 1 2 1 1 1
 6 M/C1 TTIG=  9406.10 DWT=   49.00 H-OFF=    .000 S-OFF=        .002 1 0 1 1 1
 7 M/C2 TTIG= 10073.66 DWT=   41.?0 H-OFF=    .000 S-OFF=        .002 1 0 ' 1 1
 8 BRAK TTIG= 10871.47 DWT=   49.0? DTBR =    .050 DWELL=       1.000 1 0 1 1 1
 9 PHAZ TIG1= 10527.39 DWT=   51.4? H-OFF=    .000 S-OFF=        .0?0 2 3 0 1 0
10 NCC2 TIG2= 78578.55 DWT=     .00       =     .000     =         .000 2 3 1 1 1
11 OOP  TIG3= 80030.27 DWT=   90.00       =     .000     =         .000 2 0 0 0 !
12 COEL TCOE= 81397.44 DWT=   90.00 SGN DH   3.191 R-HOR=      22.807 2 2 1 1 1
13 XFER TTIG= 84383.29 DWT=  1?3.08 H-OFF=    .000 S-OFF=        .002 2 2 1 1 1
14 M/C1 TTIG= 85121.92 DWT=   49.00 H-OFF=    .000 S-OFF=       -.002 2 0 1 1 1
15 M/C2 TTIG= 85739.97 DWT=   41.00 H-OFF=    .000 S-OFF=        .002 2 0 1 1 1
16 BRAK TTIG= 86478.60 DWT=   49.00 DTBR =    .050 DWELL=        .000 2 0 1 1 1


               REFERENCE VEHICLE LVLH SQUAREROOT COVARIANCE OF DISPERSIONS
DELTA-H          .100E+04  .000E+00  .000E+00  .000E+00 -.900E+00  .000E+00
CURV DIST        .000E+00  .321E+05  .000E+00 -.950E+00  .000E+00  .000E+00
OUT-OF-PL        .000E+00  .000E+00  .137E+04  .000E+??  .0??E+00  .000E+00
H-DOT            .000E+00 -.950E+00  .000E+00  .000E+00  .0??E+00  .000E+00
S-DOT(CO)       -.900E+00  .000E+00  .000E+?0  .000E+00  .??0E+00  .000E+00
Z-DOT            .000E+00  .000E+00  .000E+00  .000E+00  .000E+00  .260E+01


OBSERVATORY STATE(LVLH)      COVARIANCE (LVLH): OSTADM 2 HOUR FIT, 90 MIN PROP
PERIGEE     350.000  .225E+04  .?00E+00  .000E+00  .000E+00  .000E+00  .000E+00
APOGEE      350.002  .000E+00  .810?+04  .000E+00  .000E+00  .000E+00  .000E+00
LONG NODE 198.86190  .000E+00  .000E+00  .101E+04  .000E+00  .000E+00  .000E+00
INCLINATN  28.49999  .000E+00 -.950E+00  .000E+00  .000E+00  .000E+00  .000E+00
ARG PERIG    .00000 -.950E+00  .000E+00  .000E+00  .000E+00  .000E+00  .000E+00
PHASE     110.97830  .000E+00  .000E+00  .000E+00  .000E+00  .000E+00  .132E+01

TARGET 1 RELATIVE PERIOD=  .731640E+05 SEC


ORBITER STATE (LVLH)         COVARIANCE (LVLH): OSTADM 2 HOUR FIT, 90 MIN PROP
PERIGEE     159.997  .225E+03  .000E+00  .000E+00  .000E+00 -.195E+03  .000E+00
APOGEE      160.000  .000E+00  .155E+04  .000E+00 -.135E+04  .000E+00  .000E+00
LONG NODE 200.00020  .000E+00  .000E+00  .434E+03  .000E+00  .000E+00  .000E+00
INCLINATN  28.50001  .000E+00 -.184E+01  .000E+00  .211E+01  .000E+00  .000E+00
ARG PERIG    .00000 -.236E+00  .000E+00  .000E+?0  .000E+00  .272E+00  .000E+00
PHASE      89.33933  .000E+00  .000E+00  .000E+00  .000E+00  .000E+00  .132E+01
```

Figure 3-3: Planner Output Data

```
BURN 1: TIG=      .0  DVX(?)=    .00  DVY(1)=   -5.83  DVZ(?)=     .00  RSS DV=   5.83
BURN 2: TIG=  2711.5  DVX(1)=   -.06  DVY(1)=  31?.32  DVZ(1)=  119.45  RSS DV= 340.93
BURN 3: TIG=  4074.2  DVX(0)=    .00  DVY(0)=     .00  DVZ(1)=     .66  RSS DV=    .66
BURN 4: TIG=  5529.5  DVX(1)=   -.07  DVY(1)=  320.96  DVZ(1)= -119.44  RSS DV= 342.45

DHF=  -2.42  DSF= -16.71  DZF=     .00  DVCSX=     .00  DVCSY=     .00  DVCSZ=     .00

             5 CYCLES RSSXF=  46. RSSVF= .04 SUM RSS=  689.87
```

Figure 3-3a: First Rendezvous Phasing, NCC, OOP, Coelliptic

```
BURN 1: TIG= 10527.4  DVX(0)=    .00  DVY(1)=  -25.97  DVZ(0)=     .00  RSS DV=  25.97
BURN 2: TIG= 78578.5  DVX'  = -20.45  DVY(1)= -309.25  DVZ(1)= -121.45  RSS DV= 332.87
BURN 3: TIG= 80030.3  D? .0)=    .00  DVY(0)=     .00  DVZ(1)=    -.01  RSS DV=    .01
BURN 4: TIG= 81397.4  D? (1)=  21.03  DVY(1)= -297.00  DVZ(1)=  114.37  RSS DV= 318.95

DHF=   3.20  DSF=  22.81  DZF=     .00  DVCSX=     .00  DVCSY=     .01  DVCSZ=    -.04

             3 CYCLES RSSXF=  81. RSSVF= .07 SUM RSS=  677.80
```

Figure 3-3b: Second Rendezvous Phasing, NCC, OOP, Coelliptic

4.0 Universal Maneuver Processor (UMP)

The classical solution to the minimum fuel n-burn rendezvous problem has been treated by Lawden (3) and others, and shown to be a two-point boundary value problem. In Lawden's treatment, a primer vector is defined which can be shown to follow the Clohessy-Wiltshire Equations of relative motion. For an impulsive sequence, it is known that the optimal maneuver points occur at time when the magnitude of the primer vector approaches 1 from below (<1), and that the thrust direction is that of the primer vector at each such point. The boundary value problem is that of finding a solution to the primer vector equation such that the sequence of impulses result in attainment of the specified end conditions, given specified initial conditions. In general this problem cannot be solved in closed form, and a different approach is more practical. By adopting coelliptical conditions as the nominal final state of various phases of the rendezvous sequence, it can be calculated what initial phasing results in mimimal total propellant for a two-impulse transfer to a coelliptical final condition from arbitrary initial conditions. If the relative state at each point is given in terms of position, and velocity relative to coelliptical speed at that point, the resulting problem can be minimized with respect to transfer interval, which amounts to a solution to the primer vector boundary value problem. This has been done in the ORMP.

An important feature of the resulting mission plan is that dispersions in relative motion due to initial placement errors and resolved navigation uncertainties do not significantly affect the time placement of maneuvers for the optimal sequence. Such effects as occur can be dealt with by minor adjustments of the maneuver times, which do not alter the basic timeline. Therefore, it is almost never necessary to re-solve the planning problem in real time. Rather, it is only necessary to solve for a specific set of maneuvers based on the current best knowledge of the state.

From an analytical point of view then, the maneuver computation problem on a given day of execution can be characterized by a fixed number and time of burns, with specified initial and terminal conditions. This is true of both the terminal phase and pre-coelliptic phases, and since in fact the terminal phase is a special case of the pre-coelliptic phase resulting in coelliptic conditions at braking, all the optimization results derived for transfer to a coelliptic offset apply equally to the terminal phase. It is therefore possible to devise a single computational algorithm which accepts specification of the burn times and terminal constraints, and produces a minimum variance estimate of the burn solution set. Such an algorithm has been devised as described in Appendix A of this report, and incorporated into both the ORMP and the ORBNAV programs. The algorithm possesses the following important properties:

a) No computational singularities, provided that a solution for a given set of times and terminal constraints physically exists;

b) Specification of 1 to 6 terminal constraints in position and velocity;

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(3) Lawden, D.F., Optimal Trajectories for Space Navigation, Butterworths, London, 1963

c) Specification of velocity offsets with respect to in-plane coelliptical speed;

d) Specification of out-of-plane position and velocity off-sets;

e) Minimizes the squared magnitude of each component of each maneuver, and hence the sum squares of the total sequence;

f) Utilizes software functions typically provided for state and covariance propagation, and filter covariance measurement up-dating;

g) Implicitly accounts for all modelled disturbing accelerations.

It should be emphasized that these characteristics do not depend on any assumption of coelliptical initial or final conditions. The coelliptical conditions are utilized only for mission design purposes to find maneuver times and targeting conditions which are at or near the minimum total propellant points that would be identified by an exact solution of the Lawden primer vector boundary value problem. The UMP can be used to find the minimum-propellant solution to any set of fixed burn times which have been derived by any other method, whether or not known to be optimal, such as the current shuttle rendezvous baseline.

It was stated in Section 2 that the problem of station-keeping remained to be dealt with. The application of the UMP in this context is immediate and obvious: One has only to specify the desired stationkeeping position, and periodically cycle the UMP on to compute a two-impulse solution from the current to the desired position. Other approaches are possible but depend on specific and as yet undefined applications.

APPENDIX A

GENERAL SOLUTION TO THE FIXED-TIME MANEUVER
COMPUTATION PROBLEM

1. Mathematical Preliminaries

We are concerned with finding the best estimate of various vector-valued random variables. In order to facilitate the analysis, the method of ortogonal projection will be employed. Using the Dirac notation, we define

$|x\rangle = \underline{x}$ a vector-valued random variable

$\langle y| = \underline{y}^T$ the adjoint of $|y\rangle$

$\langle y|x\rangle = \underline{y}^T\,\underline{x} = \underline{y}\cdot\underline{x}$

$|x\rangle\langle y| = E(\underline{xy}^T)$ the expectation of $\underline{xy}^T$

Further, the orthogonal complement of $|x\rangle$ with respect to $|y\rangle$ is defined as

$$|\tilde{x}\rangle = |x\rangle - A|y\rangle$$

with A chosen so as to mimimize $J = |\tilde{x}\rangle\langle\tilde{x}|$:

$$J = [|x\rangle - A|y\rangle][\langle x| - \langle y|A^T]$$

in the usual way, we take the variation in J with respect to a variation in A and require the result to be identically zero for an extremum:

$$\delta J = -[|x\rangle - A|y\rangle]\langle y|\delta A^T - \delta A|y\rangle[\langle x| - \langle y|A^T] = \phi$$

which implies

$$[|x\rangle - A|y\rangle]\langle y| = |x\rangle\langle y| - A|y\rangle\langle y| = \phi$$

or

$$A = |x\rangle\langle y|\ |y\rangle\langle y|^{-1}$$

so that

$$|\tilde{x}\rangle = |x\rangle - |x\rangle\langle y|\,|y\rangle\langle y|^{-1}|y\rangle = |x\rangle - |\hat{x}\rangle$$

$|\hat{x}\rangle$ is called the orthogonal projection of $|x\rangle$ onto $|y\rangle$, or in more mundane terms, the best estimate of $|x\rangle$ given $|y\rangle$. It is straightforward to establish the following further results:

$$|\tilde{x}\rangle\langle\hat{x}| = \phi$$

$$|\tilde{x}\rangle\langle y| = \phi$$

$$|x\rangle\langle\hat{x}| = |\hat{x}\rangle\langle x| = |\hat{x}\rangle\langle\hat{x}|$$

$$|x\rangle\langle\tilde{x}| = |\tilde{x}\rangle\langle x| = |\tilde{x}\rangle\langle\tilde{x}|$$

As a practical example of the application of these results, consider an observation process where

$$|y\rangle = H|x\rangle + |n\rangle; \qquad |x\rangle\langle x| = P, \quad |n\rangle\langle n| = R, \quad |x\rangle\langle n| = \phi$$

If there is no a priori estimate of $|x\rangle$, the best estimate of $|x\rangle$ is given by

$$|\hat{x}\rangle = |x\rangle\langle y| \, |y\rangle\langle y|^{-1} |y\rangle$$
$$= PH^T[HPH^T + R]^{-1}|y\rangle$$

a familiar result. If an estimate of $|x\rangle$ has been obtained previously, we construct a new estimate as a linear combination of the old estimate and the observation $|y\rangle$. This is done by subtracting the projection of $|\hat{x}\rangle$ onto $|y\rangle$ such that

$$|\tilde{y}\rangle = |y\rangle - H|\hat{x}\rangle$$

which has the property that

$$|\tilde{y}\rangle\langle\hat{x}| = [|y\rangle - H|\hat{x}\rangle]\langle\hat{x}|$$
$$= [H|x\rangle - H|\hat{x}\rangle]\langle\hat{x}|$$
$$= H|\tilde{x}\rangle\langle\hat{x}|$$
$$= \phi$$

since by definition $|\tilde{x}\rangle = |x\rangle - |\hat{x}\rangle$ and it has been shown that $|\tilde{x}\rangle\langle\hat{x}| = \phi$. Then

$$|\hat{x}^{+}\rangle = |\hat{x}\rangle + |x\rangle\langle\tilde{y}| \, |\tilde{y}\rangle\langle\tilde{y}|^{-1}|\tilde{y}\rangle$$
$$= |\hat{x}\rangle + PH^T[HPH^T + R]^{-1}|\tilde{y}\rangle$$

Also, by direct calculation

$$P^{+} = |\tilde{x}^{+}\rangle\langle\tilde{x}^{+}| = P - PH^T[HPH^T + R]^{-1}HP$$

2.0 Fixed Time Maneuver Sequences

Let $|X_f\rangle$ be the relative state of the interceptor at t_f, and $|X_c\rangle$ be the initial state. Define

$$C_{fo} = \begin{bmatrix} A_{fo} & B_{fo} \\ \dot{A}_{fo} & \dot{B}_{fo} \end{bmatrix}$$

$$G_{fn} = \begin{bmatrix} B_{fn} \\ \dot{B}_{fn} \end{bmatrix}$$

Then for any sequence of n maneuvers $|v_i\rangle$ at times t_i, the final state is given by

$$|X_f\rangle = C_{fo}|X_o\rangle + G_{f1}|v_1\rangle + G_{f2}|v_2\rangle + - - - + G_{fn}|v_n\rangle$$

Further define

$$|d\rangle = |X_f\rangle - C_{fo}|X_o\rangle$$

$$F = [G_{f1} \quad G_{f2} \quad - - \; G_{fn}]$$

$$|V\rangle = \begin{bmatrix} |v_1\rangle \\ |v_2\rangle \\ \vdots \\ |v_n\rangle \end{bmatrix}$$

Then

$$|d\rangle = F|V\rangle$$

and further,

$$|\hat{V}\rangle = |V\rangle\langle d| \, |d\rangle\langle d|^{-1}|d\rangle$$

If no a priori statistics are available on the space of $|V\rangle$, we are at liberty to select the gauge condition $|V\rangle\langle V| = I$, so that $|d\rangle\langle d| = F|V\rangle\langle V|F^T = FF^T$

$$|\hat{V}\rangle = F^T[FF^T]^{-1}|d\rangle$$

which is the unweighted least squares estimate of $|V\rangle$. Let $U=|V\rangle\langle V|$ with an initial value $U=I$. Then we may at each point define $|d\rangle$ to be the i^{th} component of the deviation vector $|X_f\rangle - C_{fo}|X_o\rangle$, where $|X_f\rangle$ is the desired final state of the system. Thus it is possible to recursively process the constraint equation:

$$|\hat{V}_{i+1}\rangle = |\hat{V}_i\rangle + U_i\underline{h}_i[\underline{h}_i^T U_i \underline{h}_i]^{-1}|d_i\rangle \qquad i = 1, m;\ m \leq 6$$

$$U_{i+1} = U_i - U_i\underline{h}_i[\underline{h}_i^T U_i \underline{h}_i]^{-1}\underline{h}_i^T U_i \qquad |\hat{V}_1\rangle = |0\rangle$$

$$U_1 = I$$

$$\underline{h}_i = F_{1,*}$$

If the we define $D = |d\rangle\langle d|$, then the covariance of the solution vector (not the error in the solution vector) is given by

$$D = |\hat{V}\rangle\langle\hat{V}| = F^T[FF^T]^{-1}D[FF^T]^{-1}F$$

$$|\hat{V}\rangle\langle\hat{V}| = F^T[FF^T]^{-1}F$$

2.1 Conditions for Existence of $|\hat{V}\rangle$

It is apparent that $|\hat{V}\rangle$ exists if the inverse $[FF^T]^{-1}$ exists. this will be true if the matrix FF^T has full rank, i.e. its determinant is not zero. We need only examine the deterministic case, that is the case where the number of maneuver components is equal to the number of terminal constraints. If the number of components is less than the num̈ er of constraint equations, a solution will not in general exist except for unique values of $|d\rangle$. If we assume two three-asxis burns at different times, the F matrix looks like

$$F = \frac{1}{w}\begin{bmatrix} s_{f1} & 2(1-c_{f1}) & 0 & s_{f2} & 2(1-c_{f2}) & 0 \\ -2(1-c_{f1}) & 4s_{f1}-3wt_{f1} & 0 & -2(1-c_{f2}) & 4s_{f2}-3wt_{f2} & 0 \\ 0 & 0 & s_{f1} & 0 & 0 & s_{f2} \\ w(2-c_{f1}) & w(3wt_{f1}-2s_{f1}) & 0 & w(2-c_{f2}) & w(3wt_{f2}-3s_{f2}) & 0 \\ -ws_{f1} & w(2c_{f1}-1) & 0 & -ws_{f2} & w(2c_{f2}-1) & 0 \\ 0 & 0 & -wc_{f1} & 0 & 0 & -wc_{f2} \end{bmatrix}$$

Examining the out-of-plane submatrix, we see that its determinant is

$$w(s_{f2}c_{f1} - s_{f1}c_{f2}) = w\sin(wt_{21})$$

This will be zero for $wt_{21} = n(pi)$, n=0,1,2... It is further apparent that if $wt_{f1} = wt_{f2} + 2n(pi)$, that column 1 of F has the same value as coulmn 4, and that F is therefore singular. We therefore find out-of-plane singularities if all burns are n(pi) apart, and in-plane singularities if all burns are 2n(pi) apart. This condition can be observed in the recursive solution process by testing

$$\underline{h}_i^T U_i \underline{h}_i > 0$$

whereby if it fails, processing of that component should be aborted, and an indicator set to draw attention to the improper specification of the burn intervals.